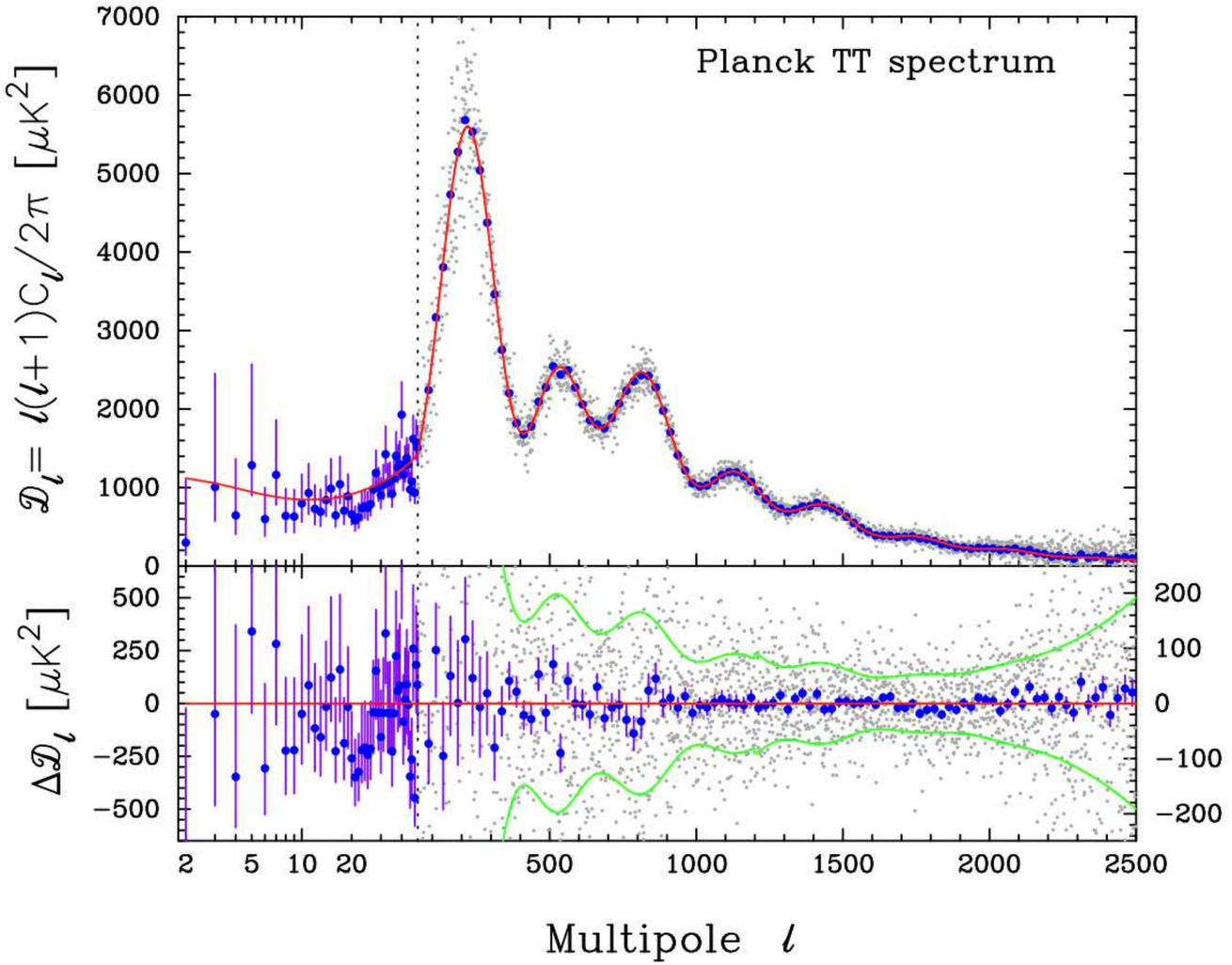
Are the missing baryons on halo scales residing in warm-hot-phase CGM

Speaker: Bo-An Chen, Yi-Shin Tsang

ESO/WFI (Optical); MPIfR/ESO/APEX/A.Weiss et al. (Submillimetre); NASA/CXC/CfA/R.Kraft et al. (X-ray)

An introduction to the missing baryon problem

The cosmological baryon budget



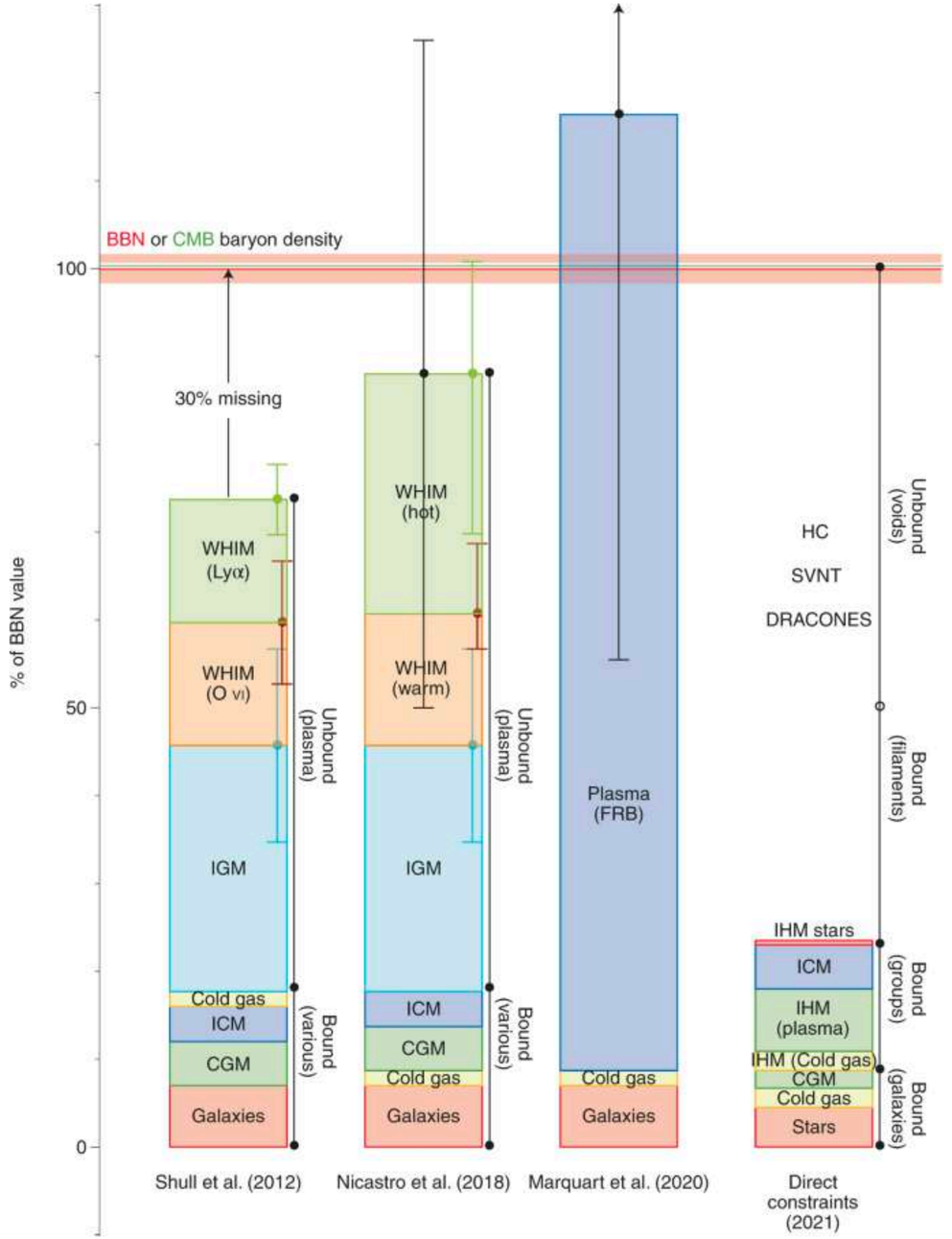
Parameter	*Planck*+WP Best fit	*Planck*+WP 68% limits
$\Omega_b h^2$	0.022032	0.02205 ± 0.00028
$\Omega_c h^2$	0.12038	0.1199 ± 0.0027
$100\theta_{MC}$	1.04119	1.04131 ± 0.00063
τ	0.0925	$0.089^{+0.012}_{-0.014}$
n_s	0.9619	0.9603 ± 0.0073
$\ln(10^{10} A_s)$	3.0980	$3.089^{+0.024}_{-0.027}$

Plank Collaboration (2013)

Missing cosmic baryons

- Stars account for only a small fraction of baryons
- We measure gas properties by spectroscopic analysis through line of sight, using Balmer lines, $Ly\alpha$, and X-rays
- There are still about 30% of baryons missing
- We assume them to be in hotter gas phase ~ 10^6 K…

Interestingly, there is no missing baryon problem on a cluster scale…



Driver, (2021)

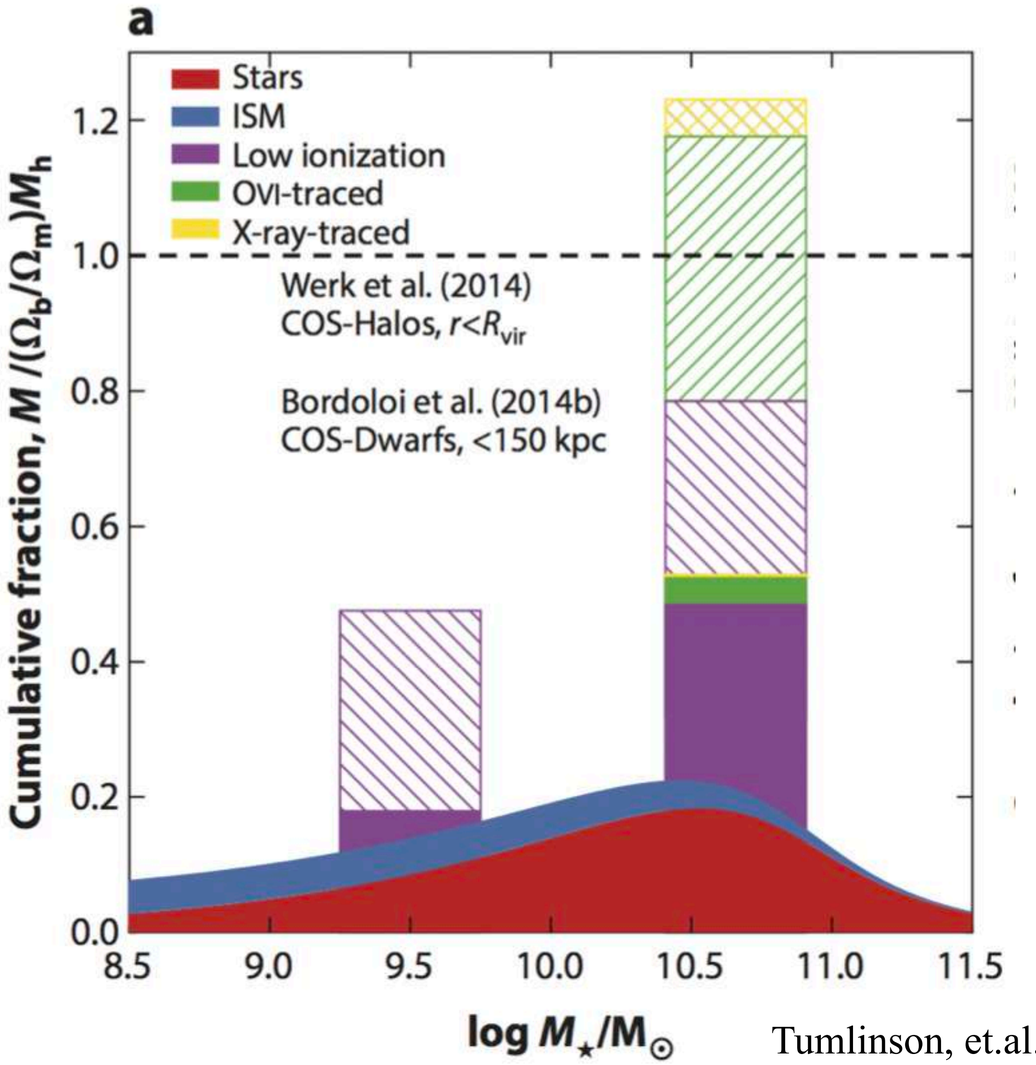
Where are the missing baryons

- On the cosmological scale (voids), warm-hot intergalactic medium (WHIM) is the candidate for residing missing baryons

- On the halo scale, circumgalactic medium (CGM) is the candidate reservoir for missing baryons

Missing baryons on halo scales

- Stars account for only a small fraction of baryons
- CGM have observed so far cannot fulfill the baryon budget
- We can first focus on halo mass at $10^{10.5} M_{\odot}$



Tumlinson, et.al., (2017)

Argument I:

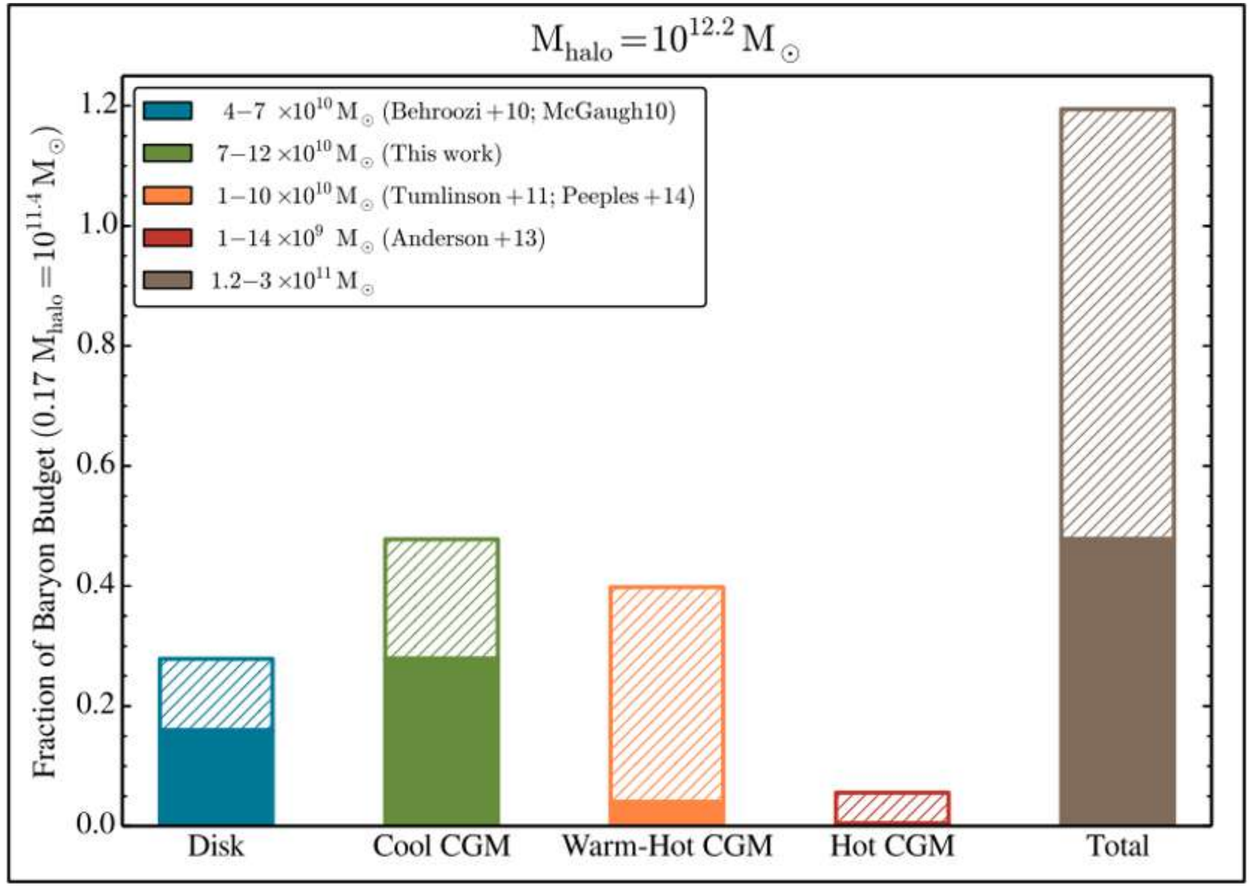
Why Warm-Hot CGM is likely to solve the missing baryons problem in halos.

Yi-Shin Tsang

Brief statement

- Baryon density can be constrained by ionization fraction, thus the fraction of baryons in different phases can be constrained

- Among all phases, warm-hot CGM may account for largest portion of missing baryons.

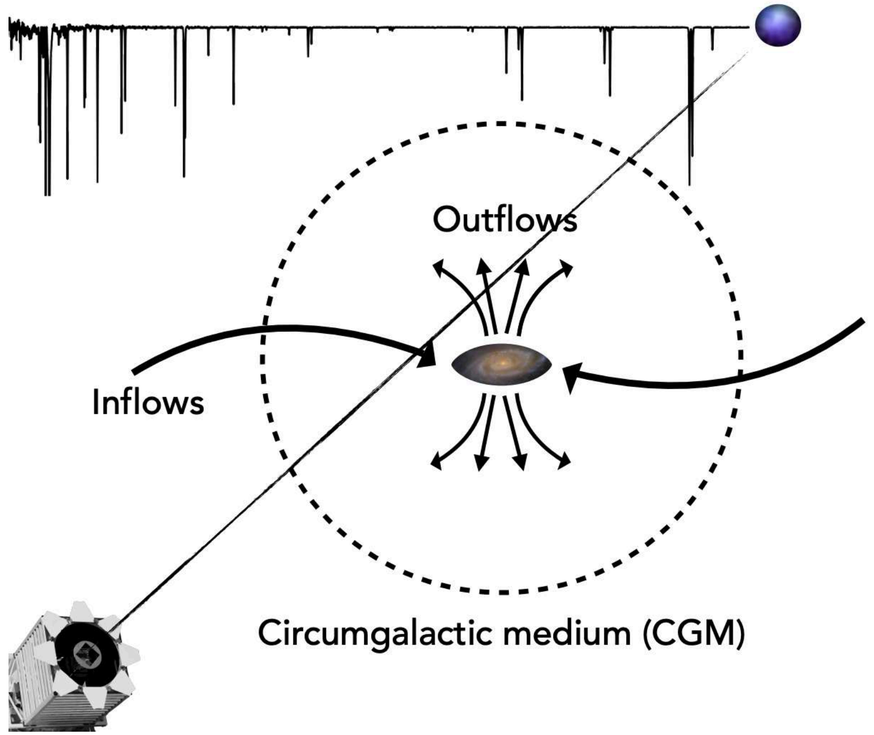


Werk, et.al., (2014)

Methods for observing CGM

- Line of sight between quasar, halo, and the Earth
- Convert spectroscopic intensity into column density
- Infer CGM mass from column density with impact parameter – virial radius ratio

Assumption:
Halo gas in ionization equilibrium,
so that line of sight method is available

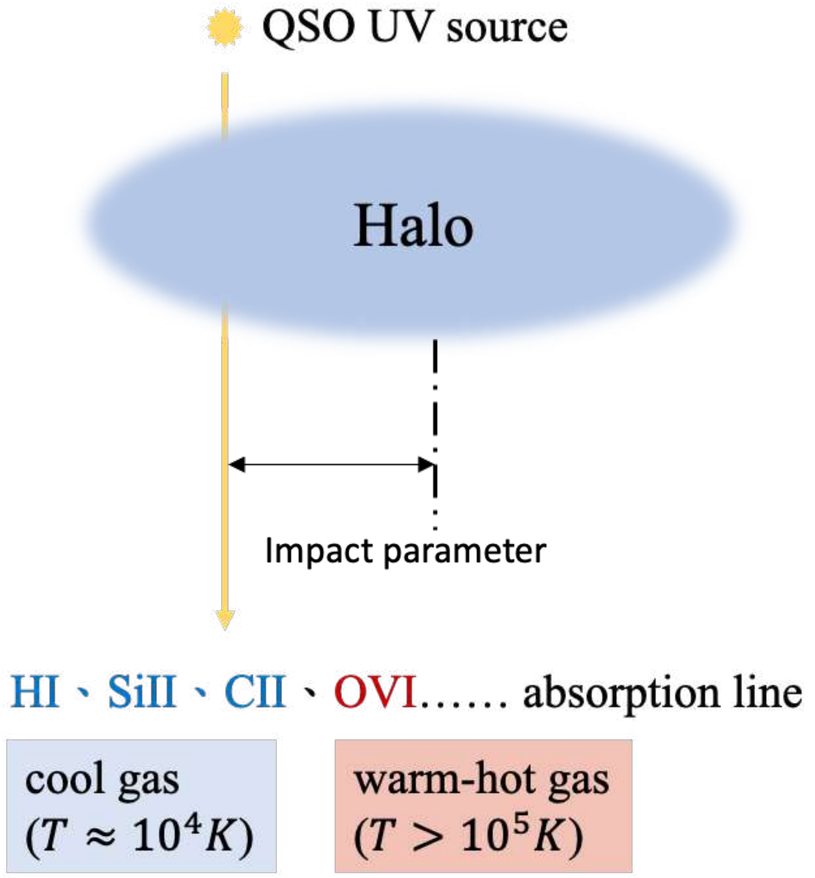


Lan, et.al., (2020)

Why might a majority of missing baryons be found in Warm-Hot CGM?

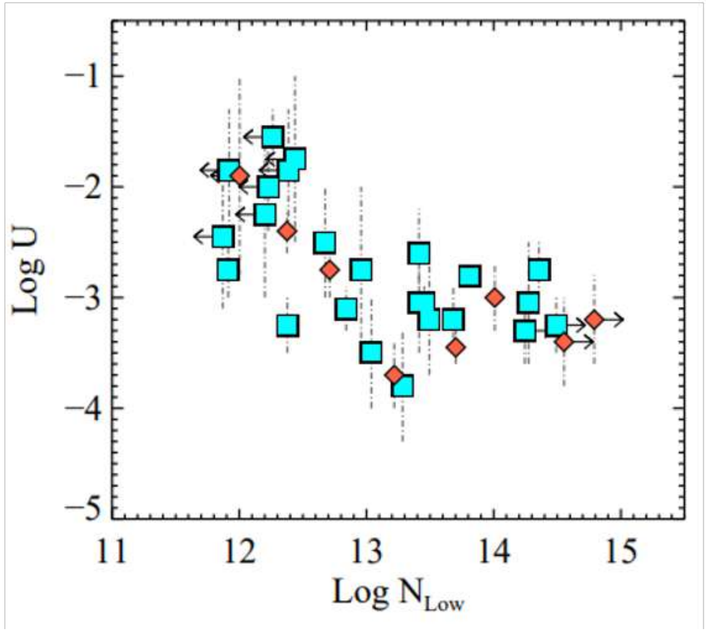
Previous Challenges to observe warm-hot phase CGM

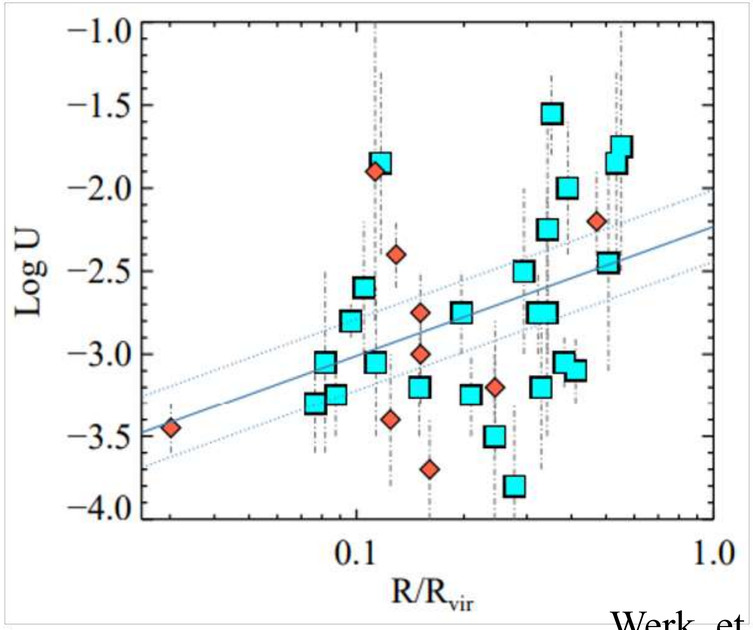
- The Sunyaev–Zeldovich effect requires high angular resolution
- Highly ionized gas requires high resolution $Ly\alpha$ and X-rays observation
- Sources of O VI line is difficult to identify.



How was the lower limit of existing baryons constrained?

$$N = N_{ionized} + \frac{1}{1-\chi} N_{ionized} \qquad \chi : ionization\ fraction$$





Werk, et.al., (2014)

Ionization parameter as a function of ion column density
(By CLOUDY photoionization model based on COS-Halos observation)

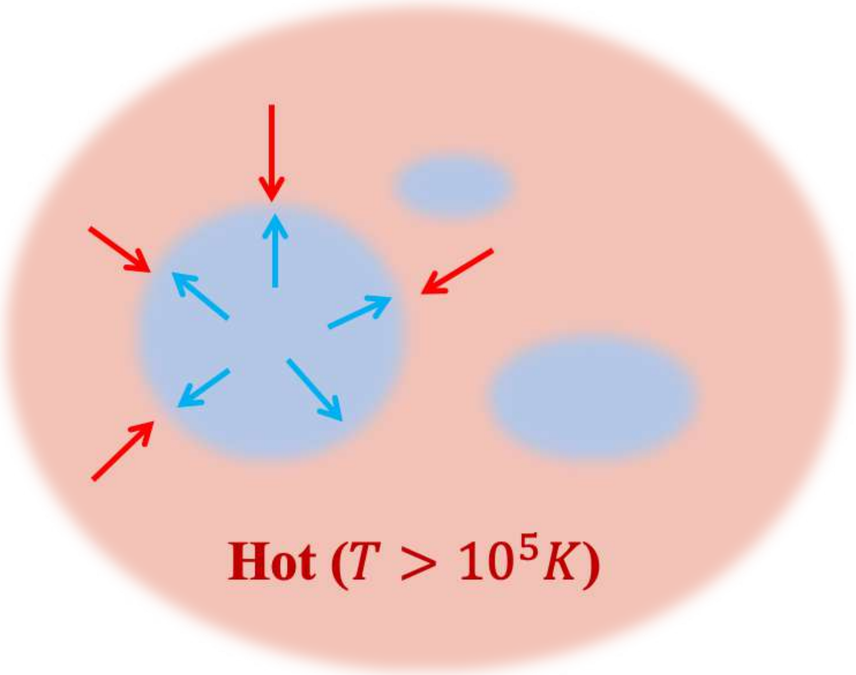
Ionization parameter as a function of Impact parameter(R)
(By CLOUDY photoionization model based on COS-Halos observation)

Two phase model – potential degeneracy?

Why different phases in **ionization equilibrium**? Not pressure equilibrium?

Two-phase halo model reproduces the density profile of hot phase gas.

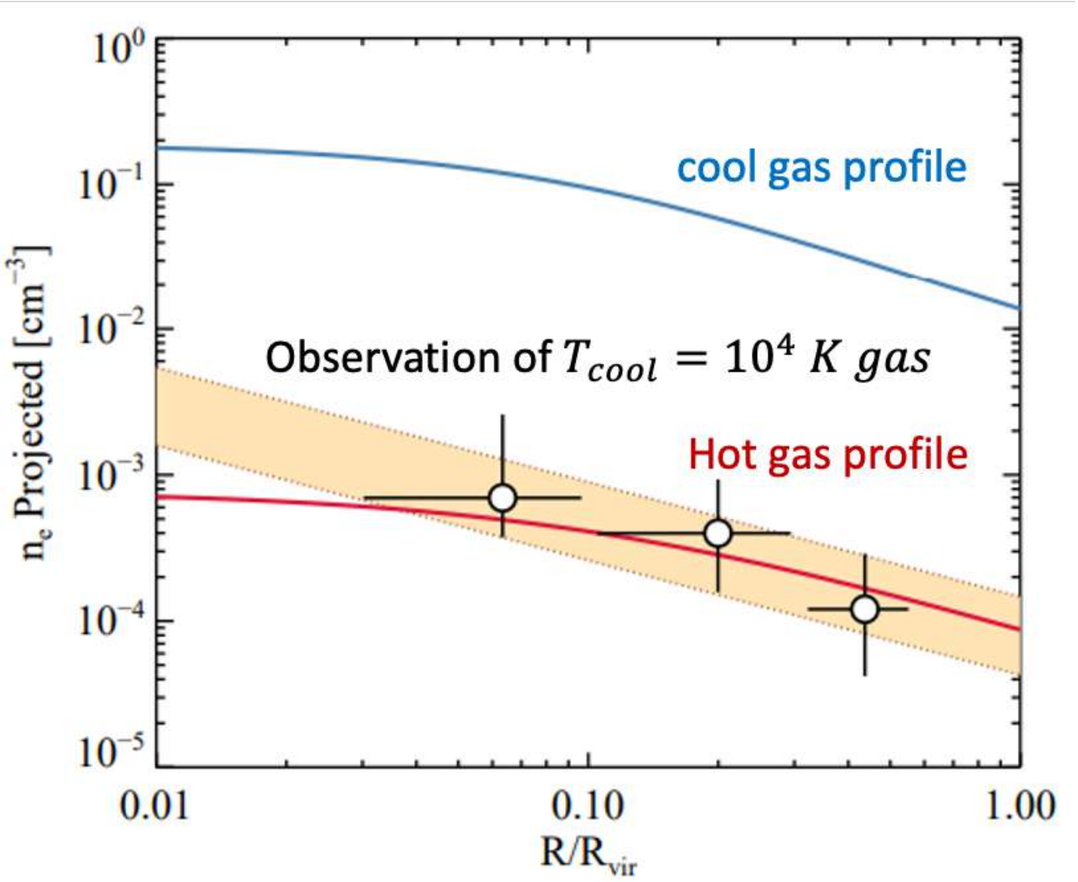
Mo & Miralda-Escude (1996)



Falsify the two phase model

$$\begin{cases} \rho_{cool}(r) = \rho_H(r)\dfrac{T_h(r)}{T_{cool}(r)} \\ \rho\,(R) = \dfrac{\int \rho^2(r)ds}{\int \rho(r)ds} \end{cases}$$

There's no clumpy cool gas in pressure equilibrium, or what we observed cool would be hot!



Werk, et.al., (2014)

Conclusion

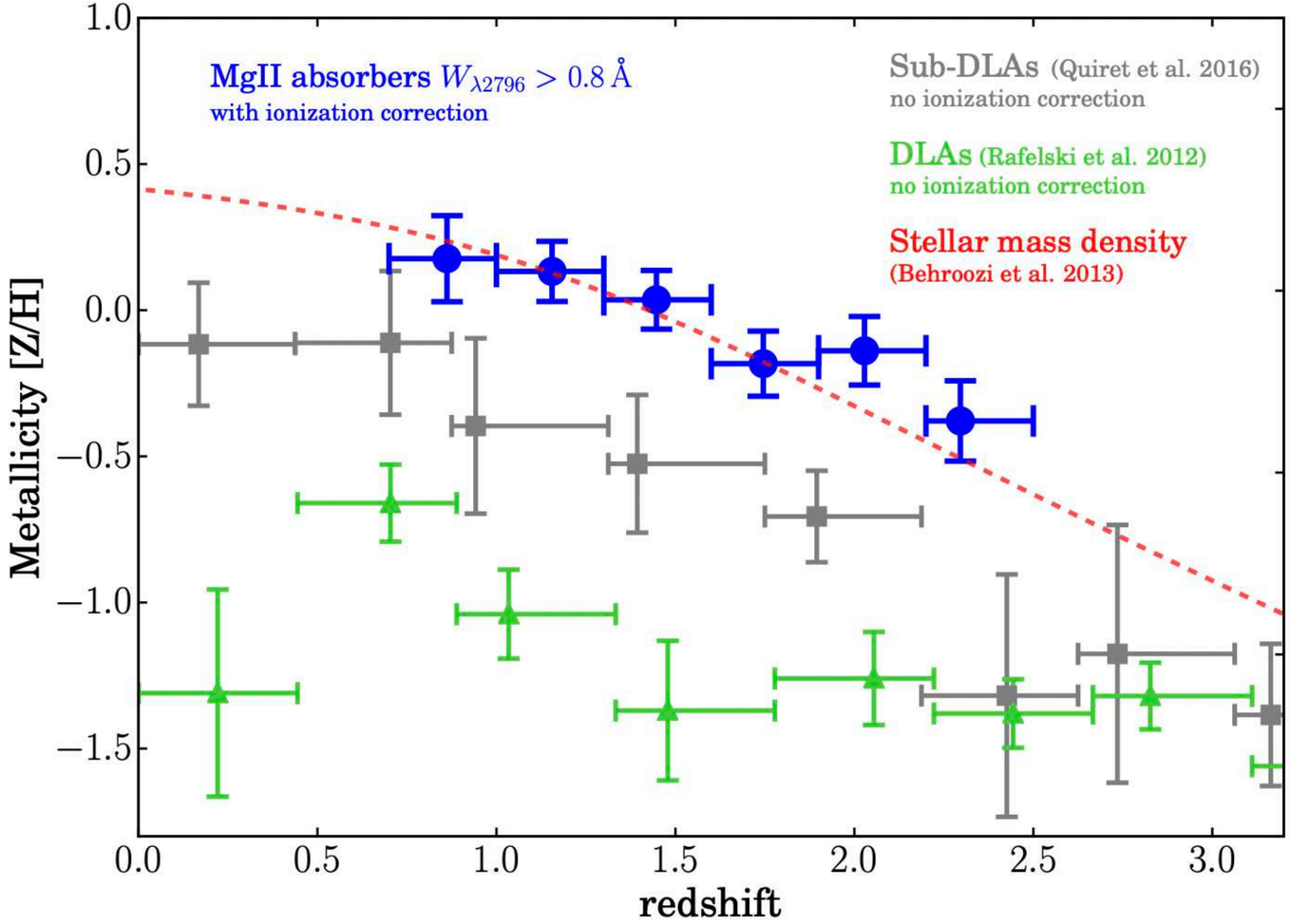
- L.O.S method still robust.
- Ionization parameter – impact parameter relation gives reasonable constraint of potentially existing missing baryons.
- Missing baryons mainly in **warm-hot CGM**, which is underestimated in the past

Argument II:

The missing baryons are hidden in low ionization phases based on a more complicated phase model

Bo-An Chen

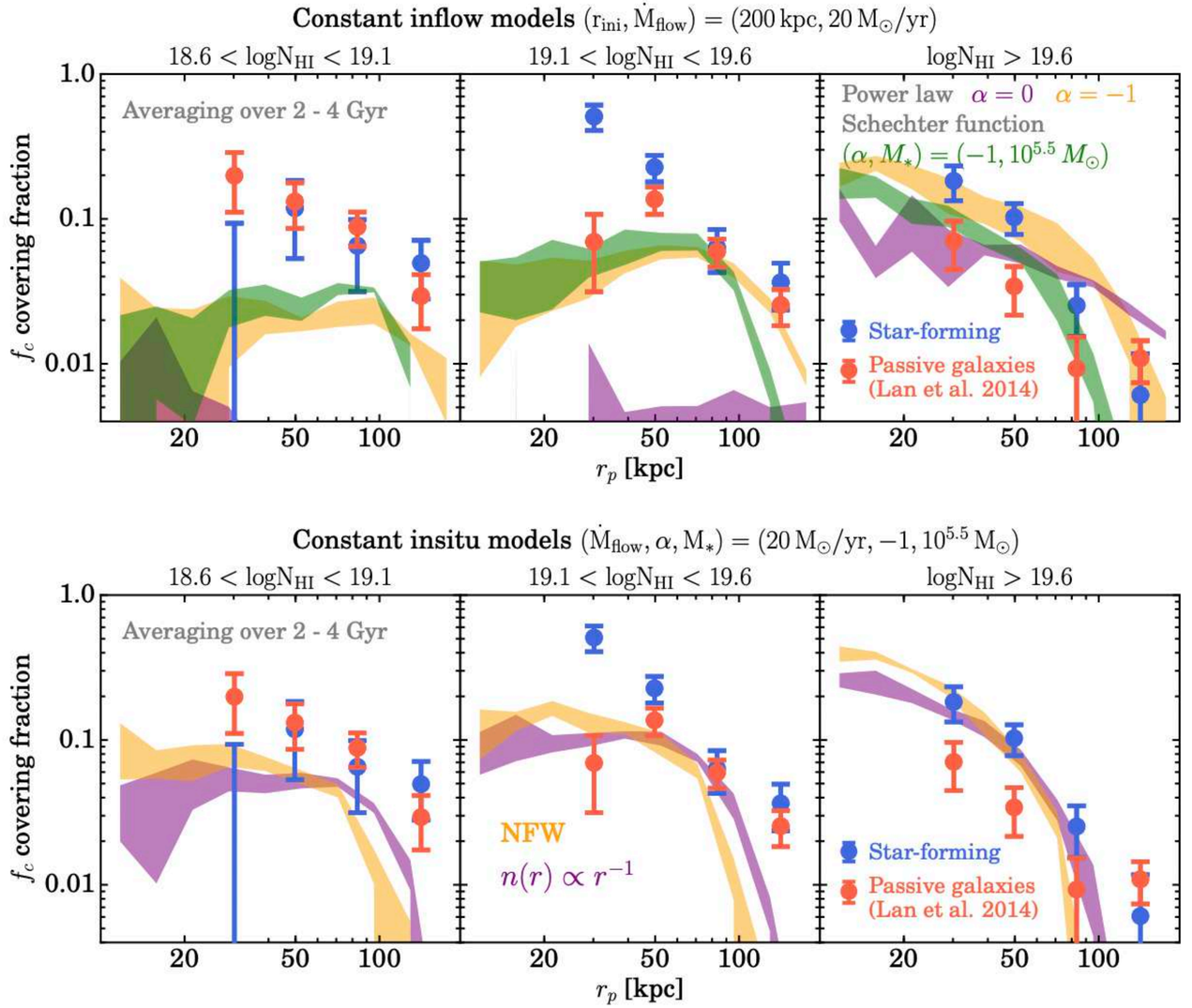
Properties of the low ionization phase



Lan & Fukugita (2017)

Properties of the low ionization phase

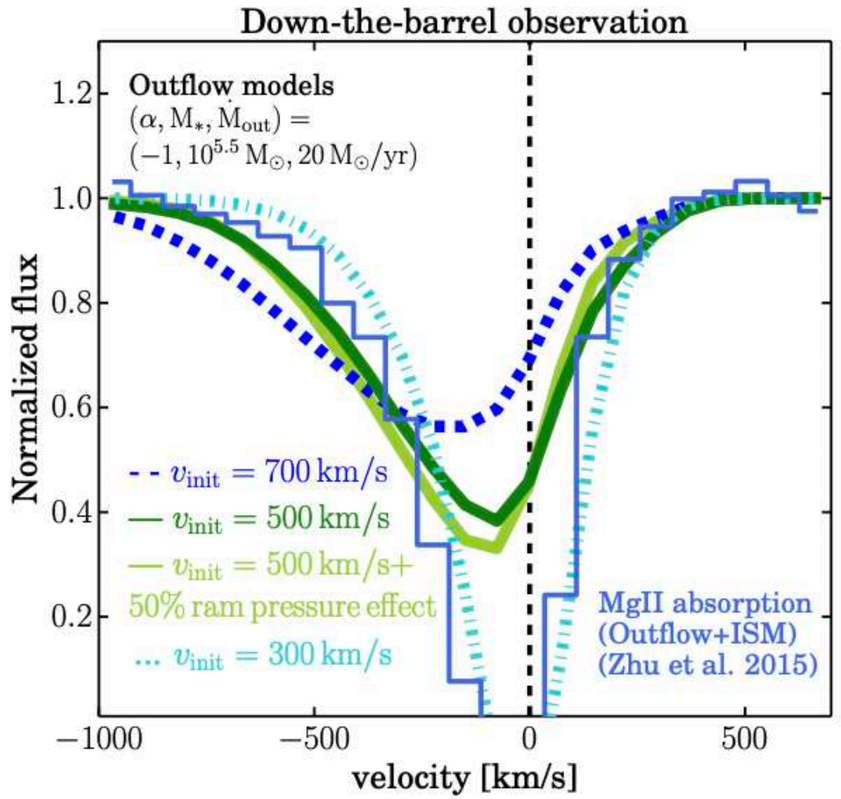
Inflow model

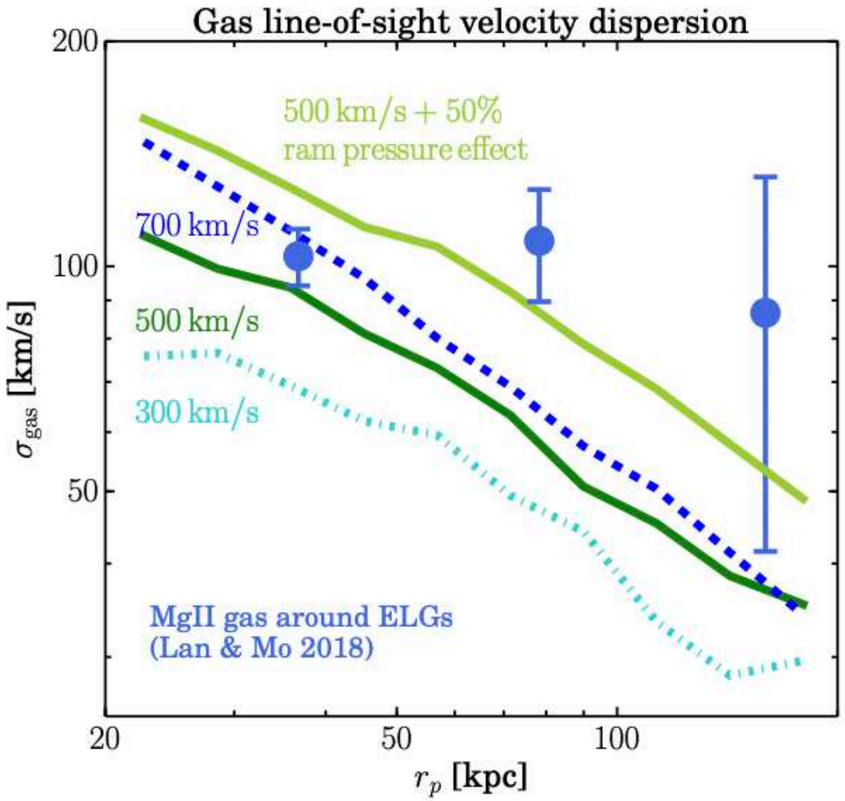


Lan & Mo (2019)

Properties of the low ionization phase

Outflow model





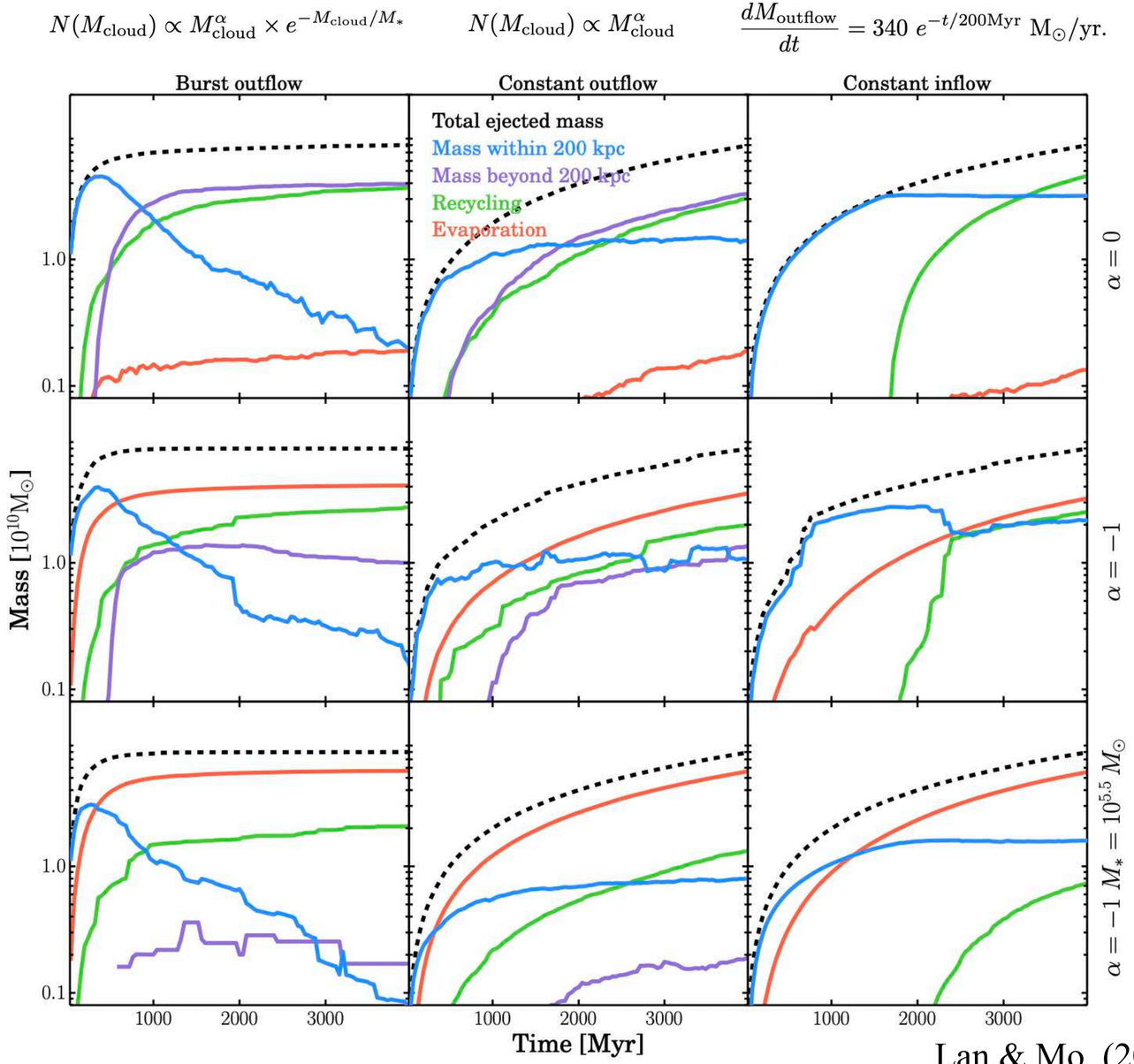
Lan & Mo (2019)

Consequences of the outflow/inflow model

- Recycling low ionization phases
- Axi-symmetry of the low ionization phase
- Mis-assigned low ionization phases

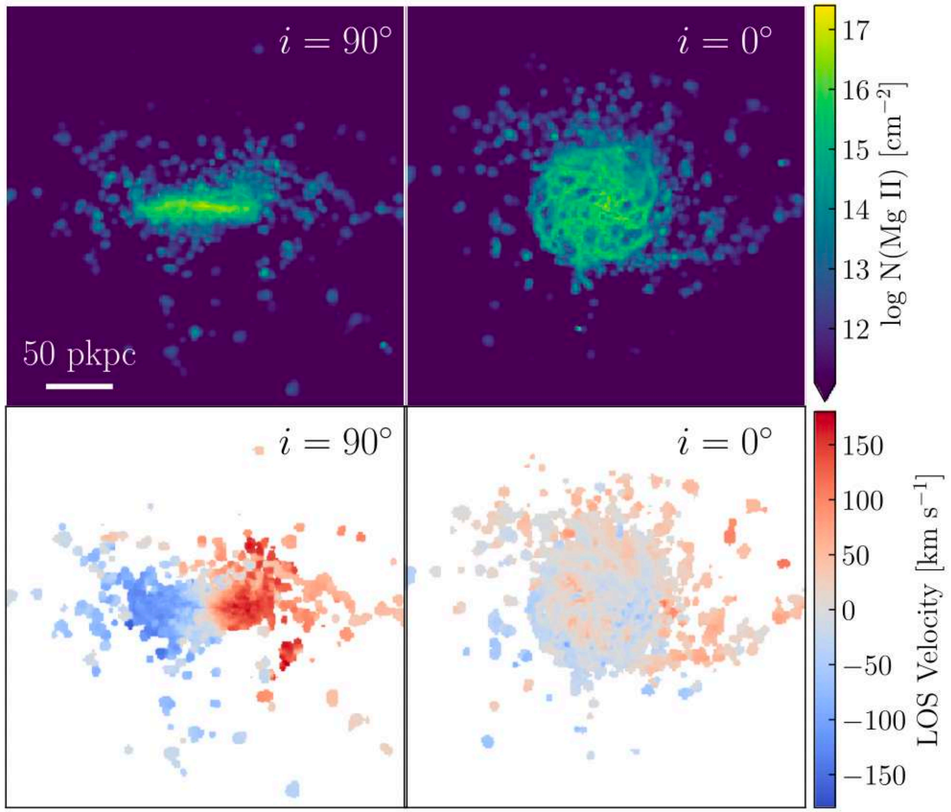
Recycling low ionization phases

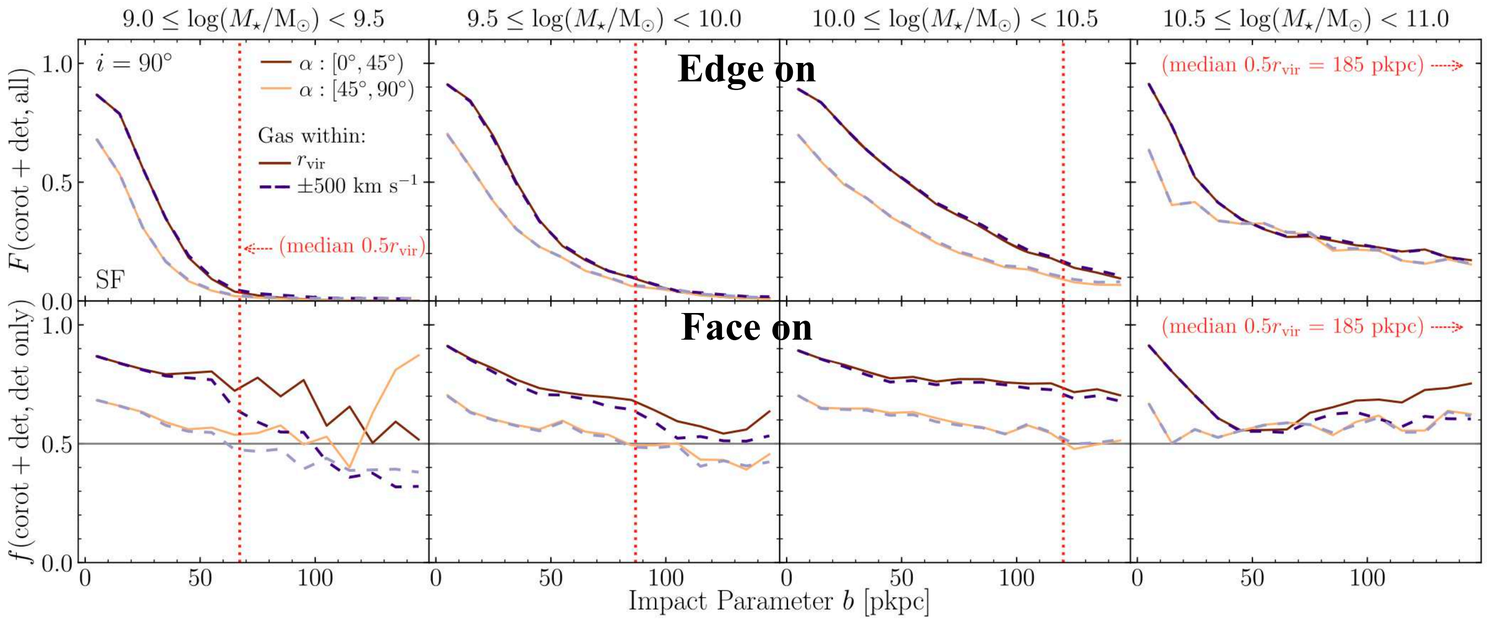
- Recycling gas could occur on a large time scale
- A small fraction of mass remains in the halo (15%) or gets evaporated (5%) (for some initial cloud mass function)
- The total mass in the (cool) CGM depends on the shape of the initial cloud mass function



Lan & Mo (2019)

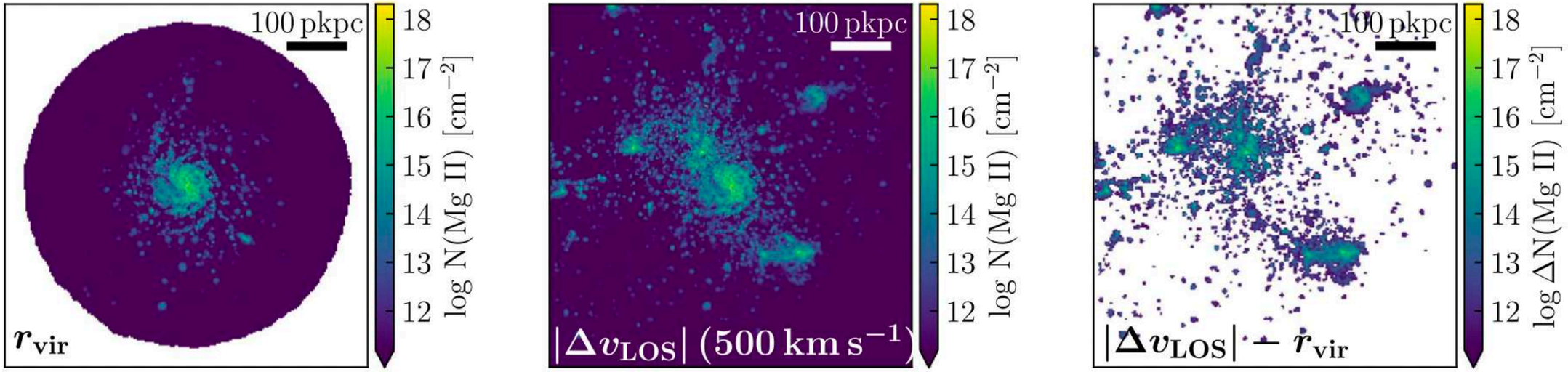
Axi-symmetry of the low ionization phase





Ho, et.al., (2020)

Mis-assigned low ionization phases



Ho, et.al., (2020)

Mg II gas within r_{vir} (left)

Mg II gas within the ±500 km s^{-1} LOS velocity window (middle)

The column densities of these extra Mg II structures exceed the Mg II detection limit (right)

LOS would have associated these structures with the target galaxy.

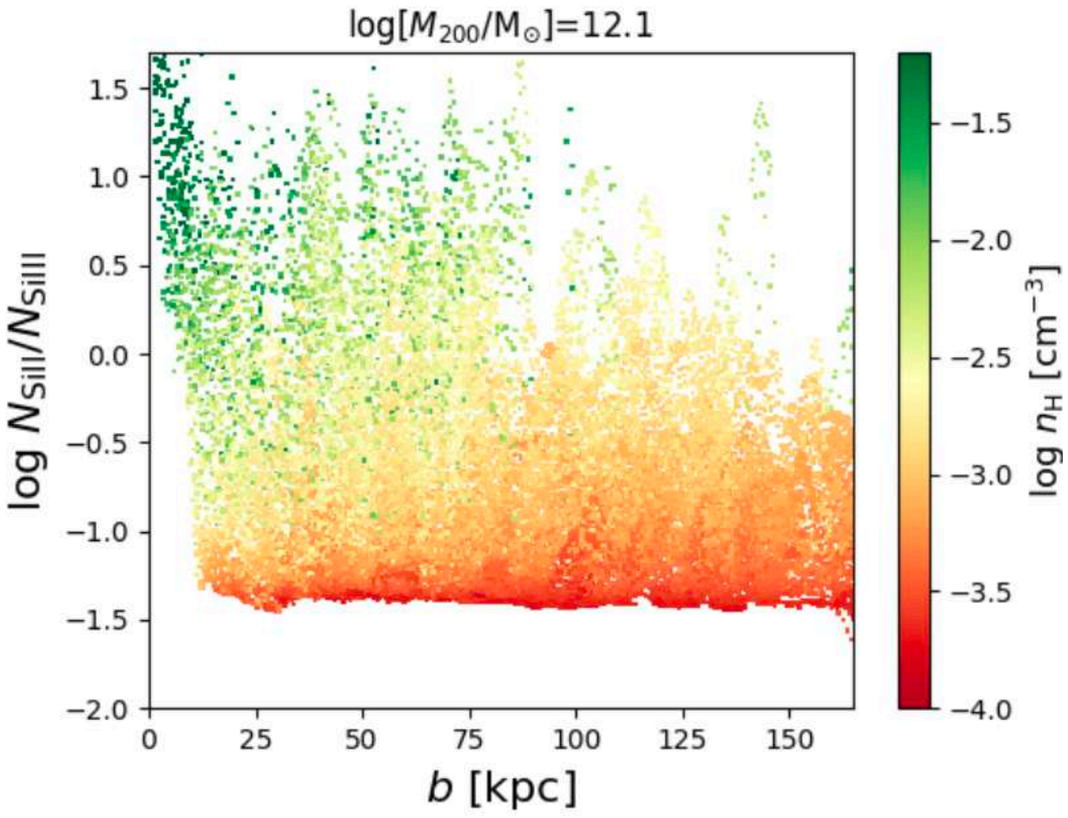
The contribution of low ionized cool-phase CGM is underestimated !

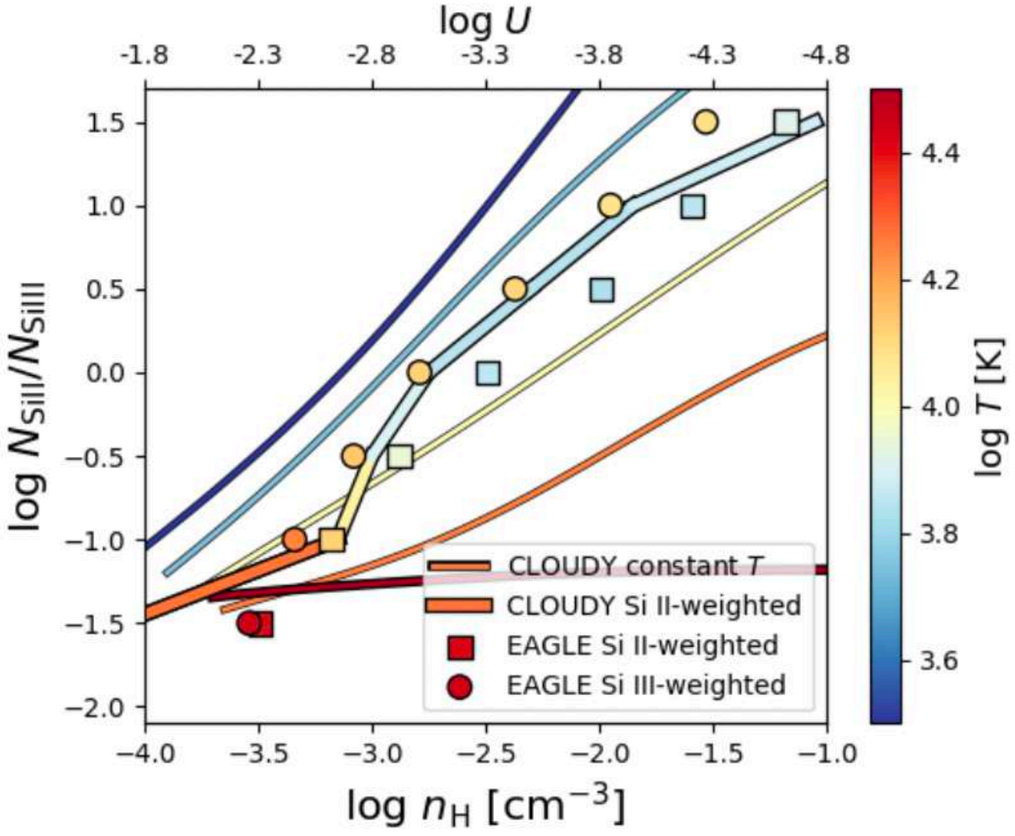
Challenges against Warm-hot-phase CGM

A quick review on the assumptions…

- Photoionization dominates
- The absorption lines of all low ionized phases originate from the same space
- Ionization equilibrium

Ionization and impact parameter scattering

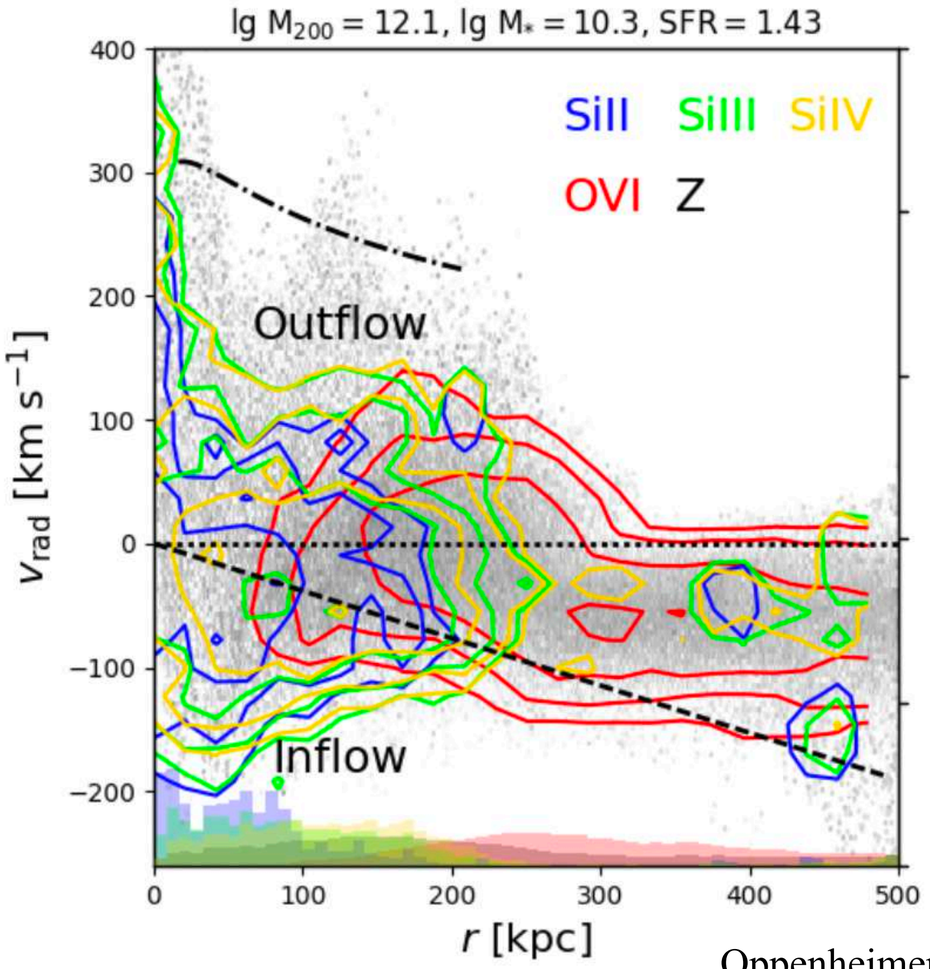




Oppenheimer, et.al., (2017)

Ionization equilibrium or pressure equilibrium

- AGN is considered in the model
- Inflow and outflow contribute to dynamical phase structure
- Denser clouds are generated in EAGLE simulation



Oppenheimer, et.al., (2017)

Concluding remarks (Yi-Shin)

- Ionization constraint is valid for baryon abundance, including warm-hot-CGM
- By improving observation techniques in X-ray and SZ-effect, we can revise the abundance of warm-hot-CGM
- The ionization profile is constrained and well fit by electron density with warm-hot-CGM

Concluding remarks (Bo-An)

- The assumption of ionization equilibrium may not hold
- Cool gas in shielded and disk structure are supported by observations and simulations
- Larger and denser cool CGM clouds could exist